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Conveying Looming with a Localized Tactile Cue

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14. ABSTRACT

Specific visual and auditory cues convey the approach of moving objects (looming). This first experiment evaluated whether tactile stimuli can convey looming. We determined whether subjects could interpret a varying vibration cue as a meaningful tacton, i.e., a simple, structured message consistent with looming. Subjects (N=35) experienced various vibration stimuli and judged (e.g., via semantic differentials) whether they could be interpreted as consistent with "approaching" or "receding." Vibration frequency and on/off beat speed of vibration were the main stimuli studied. Results indicate that increasing the frequency of vibration over the period of stimulation was most effective in conveying a tacton consistent with looming. The best stimulus was also the one most analogous to the natural Doppler shift cue, which is used in the auditory domain for detecting looming. Beat speed has been exploited in some past tactile applications to convey closing distance, but frequency may be a more ecologically-valid cue. The general findings are consistent with past research that has implied looming as a modality-neutral response.

15. SUBJECT TERMS

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Introduction

Avoiding collision with objects during self or object motion is an essential survival skill. Looming objects approaching one's face often elicit an immediate and reflexive response, which emerges early in the life span and includes protective reactions such as eye closure and raising of the hands (Kayed and van der Meer, 2000). This protective reaction depends upon specific visual, auditory, somatosensory (tactile and kinesthetic), and vestibular cues, which are mediated by common neural centers (Graziano and Cooke, 2006). Such multisensory processing mechanisms are important to the perception of the approach of moving objects towards oneself or one's own movement towards obstacles or targets, even in situations of less immediate (or more abstract) threat, in which case protective reactions to collision are not elicited.

Vision and audition are the modalities most often studied in relation to looming. Looming objects are indicated visually by systematic optical flow information such as rate of image dilation (Lee, van der Weel, Matejowski, Holmes, and Pettigrew, 1983), the neurophysiologic substrate of which has been described (e.g., Merchant and Georgopoulos, 2006). Auditory cues are also important to looming. Many animals can sense auditory changes in received frequency and amplitude (Shaw, McGowan, and Turvey, 1991; Grosse, 2009) caused by approaching sound sources. An approaching object can emit sound due to its vocalizations and/or noises associated with ground impact, friction, or engine vibrations (Schiff and Oldak, 1990). Auditory cues for looming are not as thoroughly studied as visual cues for looming, but evidence indicates that blind subjects can use appropriate acoustic cues for judging the approach of objects as accurately as sighted subjects employ visual cues (Schiff and Oldak, 1990). Similarly, bats use sound cues concerning looming in the same way birds use visual cues (Lee et al., 1992) and bats fly with comparable speed and precision (Lee, 1990).

Overall, the pattern of findings in the literature implies the probable existence of a modality-neutral looming response consistent with a general underlying perceptual mechanism (Gordon and Rosenblum, 2005; Bicchi, Scilingo, Ricciardi, and Pietrini, 2008). The question arises as to whether a similar response occurs in the tactile domain. Acoustic and vibrotactile frequencies are known to be perceptually associated and are compatible stimuli (Ocelli, Spence, and Zampini, 2009), but it is not known whether the looming response described above extends to modalities other than audition or vision. The experiment in this report took the first step towards addressing this issue by conducting an exploration of subjects' basic reactions to several simple, localized tactile stimuli (conveyed by small vibrating tactor units) to determine if simple tactile stimuli can convey the meaning of approach to/by an object.

While there has been little research specific to this topic (Shiff and Oldak, 1990), it is logical to suppose that tactile displays will be effective in conveying approach to/by an object. Many animals (such as certain species of insects, fish, crustaceans, and nocturnal, burrowing, or marine mammals) have developed tactile sensors on their heads (antennae or vibrissae) to guide their movements and help them avoid collisions, negotiate passageways, and intercept or escape from targets of interest. Moreover, somatosensory (i.e., tactile and kinesthetic) cues aid with the appreciation of body movement and interception with environmental targets, since organisms must be aware of whether (and in which direction) they are slipping (or their skin is shearing) relative to surfaces or objects (Wasling et al., 2005). For example, an arboreal or terrestrial animal must correct after momentarily losing its grip or footing relative to a support surface or attempting to grasp a significant object (such as a branch or a prey animal). Similarly, an aquatic animal must judge the flow of water, plants, or terrain features across the surface of its body and accurately monitor its own success at intercepting targets or evading predators or antagonists.

As with the other animals, humans receive a plethora of environmentally-generated somatosensory cues concerning their self motion through the world (Lawson, Sides, and Hickinbotham, 2002). These include wind or water flowing around the body, ground and engine vibrations (Riecke, Fuereissen, and Rieser, 2008), forces on the body generated by acceleration, the sensed degree of body leaning and reflexive head righting required at different speeds of linear or angular motion, the angle of contact of the foot to the substrate (e.g., to avoid foot slippage), joint/muscle forces during locomotion, and the rhythmic information available during changes in locomotory speed (Guedry, Rupert, and Reschke, 1998; Gray, 2009; Williams and Weigelt, 2002; Savelsbergh and Whiting, 1996). In fact, somatosensory cues concerning impending accidental collision or intentional interception can be considered the final and most critical source of information modifying motor actions and for updating sensorimotor calibrations during the hundreds of looming judgments made daily during human maturation, or even during adult learning of any new motor skills involving object interception or avoidance (Savelsbergh and Whiting, 1996; Kayed and Van der Meer, 2009; Fajen, Riley, and Turvey, 2008). When vision is degraded, tactile information becomes very important to an adult even when locomotion is occurring through a very familiar environment (such as the home). For example, during an evening power failure in one's home, the hands are raised protectively and hands and feet are used to feel forward, in order to be warned of obstacles and passages.

Moreover, when people are deprived of a normal sense of touch in their feet, they have difficulty balancing and walking (Menz et al., 2004). Humans are even able to use remote tactile information from canes to aid their locomotion (Patla, Davies, and Niechwiej, 2004). Given the functional relevance of touch to self-motion in these situations, it is no surprise that neurophysiological evidence suggests that certain motion processing areas of the brain that respond to visual field motion are activated by tactile motion information as well (Soto-Faraco, Kingstone, and Spence, 2003).

Tactile stimuli can also modify ongoing perceptions of orientation and self-motion (Lawson, Rupert, Guedry, Grissett, and Mead, 1997; Lackner and DiZio, 2005). For example, Lackner and Graybiel (1978) reported that somatosensory stimuli systematically altered vestibular illusions of motion associated with off-vertical rotation and perceptions of self orientation during the weightless phases of parabolic flight. When subjects are stationary inside a slowly rotating optokinetic drum in complete darkness, they may still perceive illusory self-rotation when they touch the rotating surrounding cylinder and follow its motion with one hand such that their arm moves about the shoulder joint (Brandt, Büchele, and Arnold, 1977). This illusion is tactile and kinesthetic in origin. The illusion is not as readily elicited at higher velocities of drum movement when the subjects reach out and followed the drum's interior by "walking" both hands along alternately. Nevertheless, it is known that actively stepping with the feet along with the motion of a platform can enhance the perception of self-motion (Bles, 1981; Bles and Kapteyn, 1977; Riecke et al., 2011). It has been conjectured (Lawson and Riecke, 2014) that ecological considerations may contribute to this difference in findings, since rhythmic leg motion relative to a horizontal support surface is closely associated with self-movement over the stationary ground.

The most ubiquitous and versatile tactile displays currently available rely on arrays of small vibrators (called vibrotactors) on the body. It would be interesting to determine whether artificial *vibrotactile* (vibrating touch) displays can modify or elicit self-motion perceptions as well. This is not a given, since such tactor arrays are typically very small compared to the number of optical texture elements available from even an inexpensive and small computer monitor, which means that some user error will be a function of resolution of the display rather than whether the display was tactile or visual (van Erp and Verschoor, 2004). Moreover, the activation of successive pixels on a visual screen can occur with very little interstimulus delay, eliciting a sensation of smooth visual motion, whereas vibrotactors take more time to ramp up and down and the sensation of tactile flow is likely to be more like staccato rather than real tactile flow experienced in the natural world (e.g., trailing one's fingers along a wall while walking in the dark). This is likely due to the small number of vibrators in an array and the vibrators' speed of activation, rather than an inherent limitation of the cutaneous senses. In fact, it is probable that visual and cutaneous senses both have a similar ability to convey the idea of continuous apparent motion when two stimuli are presented in rapid succession, and that the interstimulus interval at which this sensation occurs is similar for vision and touch (Sherrick and Rogers, 1996; Lakatos and Shepard, 1997). Overall, the literature suggests that vibrotactile displays can be helpful when used as alerts to augment visual displays and to provide waypoint information in conditions of low visibility or difficult terrain (Prewett et al., 2012).

Although the resolution of current tactile displays is primitive compared to visual displays, there is evidence that vibrotactile flow fields can be exploited to modify feelings of self-motion. Kolev and Rupert (2008) reported that vibrotactile flow could modify a visually-induced illusion of self-motion. The authors employed a vibrotactile belt (an array of eight vertical columns of tactors around the torso, with five tactors in each column) that activated successive tactors (two columns at a time) in the opposite direction from the rotation of an optokinetic stimulus. By this means, the stimulus emulated natural tactile flow, which tended to weaken the subjects' ($N = 12$) visual vection illusion of moving in a direction opposite to the optical flow produced by real motion of an immersive optokinetic sphere. Also, 55 percent of the subjects showed evidence of an alteration in their visually-mediated optokinetic gaze reflexes when the tactile flow was activated. Similarly, when subjects ($N = 7$) were presented with simulated optical flow cues (radial expansion of ~1,000 random dots on a 20-inch monitor) for forward self-motion, their estimates of the speed of illusory forward self-motion could be reduced or increased by varying the speed of front-to-back tactile flow (i.e., inter-stimulus interval of tactor activation in a 4 by 5 array of tactors) across the seat of their pants (Amemiya, Hirota, and Ikei, 2013), which is a very natural way to convey self-motion tactually.

While natural somatosensory cues clearly are important to the ability to intercept targets or avoid obstacles, it has not been fully determined whether an *artificial* tactile display can convey useful moment-by-moment (graded and dynamic) approach information (e.g., relative distance updates) *prior* to actual contact, as has been reported for visual and auditory displays. A few studies have been performed that address vibrotactile distance-to-target cues (e.g., Jansson, 1983; van Erp, 2007; Singh et al., 2010). From such studies, it appears that subjects can interpret a spatiotemporally-varying vibration stimulus as a cue concerning the approach of a target. In 2013, more specific and complete evidence emerged stating vibrotactile flow fields may be useful for conveying looming (Cancar, Diaz, Barrientos, Travieso, and Jacobs, 2013). Cancar et al. asked 12 subjects to estimate time-to-contact of a radially-expanding tactile or visual flow field representing a simulated sphere approaching. Tactile flow was produced by radial activation of an array of vibrotactors, which “expanded” from 4 to 12 to 36 active tactors in an ovoid pattern across the abdomen. The visual flow was a computer monitor representation of the tactile flow field. This experiment found good accuracy in predicting the time-to-contact and in fact, did not detect significant differences between the visual and tactile conditions. In a second study in the same paper, the authors reported that similar tactile flow cues concerning the approach of a real ball were sufficient to enable subjects ($N = 12$) to hit the ball at the correct time in 71 percent of the trials.[1] The expanding tactile flow field Cancar et al. (2005) employed has two possible advantages over a simple on/off vibratory “looming warning cue” (such as the vibrating mode of a cell phone). First, the expanding flow field is a logical analogue of an approaching optical target or three-dimensional auditory target. Second, the perceived magnitude of the stimulus will increase as more tactors are activated (Cholewiak, 1979), thus increasing saliency (and possible urgency).

Employing a tactile array in a way analogous to optical looming is interesting and could be very useful, but it is not essential for a tactile looming cue to be an analogue of visual looming. There will be display needs where a smaller, cheaper, easier-to-implement tactile cue will be desirable. Between a full-featured tactile array and a primitive on/off tactile warning cue, there lies the intermediate possibility for a tactile display inspired by the auditory cues for looming. Blind people can detect when an automobile is rushing towards them at an intersection because the sound of the vehicle’s engine and tires seems louder and higher in pitch as the vehicle approaches nearer. Such auditory looming cues activate motor planning areas of the brain differently from receding auditory stimuli (Seifritz et al., 2002).

The perceived time to arrival of a rapidly-approaching visual or auditory object has been characterized in ecological psychology by a simple mathematical description—the rate of image dilation or change in noise intensity given by *tau* (Lee, 1976; Shaw, McGowan, and Turvey, 1991).[2] This has practical implications for display design; e.g., Gray (2011) reported that an auditory vehicle collision warning that increases in sound intensity in a way analogous to a real sound source approaching aids faster initiation of braking than any other cue he tested, with the exception of the sound of a car horn (however, the car horn produced a greater likelihood of false positive braking responses). Since simple loudness and pitch changes can help to convey looming, the lead author of the present report wondered whether a localized tactile stimulus of varying vibration frequency could convey information consistent with looming even when the tactile stimulus cues did not vary spatially over the surface of the body.

The present research sought to determine whether subjects could interpret a tactile vibration pattern cue as communicating the concept of looming or approach when the cue emanated from a small, localized body site in a manner consistent with a simple, structured message or “tactile icon” or “tacton” (Brewster and Brown, 2004) meant to convey the concept of looming. The

[1] The arc of trajectory of the ball was known to the subjects, but not its time of contact.
[2] Note that other visual and auditory factors are important also (Guski, 1992; Hancock and Manser, 1997).

intention was to evaluate subjects' perceptions of a change in vibration frequency (in Hz) or a change in the on/off pulse speed (in vibration pulses per second), since these two stimulus qualities constituted rough analogues for the change in frequency of an approaching sound source (a proven cue for looming). The basic science question was, "Can looming be conveyed by modalities other than vision or audition?"

Consideration of the optimal vibration stimuli

The vibratory frequency sensitivity of human skin ranges from about 25 to 350 Hz (Cholewiak and Collins, 1991; Greenspan and Bolanowski, 1996). Lower or higher stimulus frequencies have been tested (e.g., Bolanowski, Gescheider, and Verrillo, 1994), but require high stimulus amplitudes produced by larger vibrators and are, therefore, generally impractical for transition to low power, miniature, and/or wearable cueing systems. Nevertheless, the physical intensity of vibration must be strong enough to stimulate regions of the body typically used in wearable displays (such as the abdomen). In fact, the fingertips are ten times more sensitive to vibration than the abdomen (Weinstein, 1968; Wilska, 1954), but are a less practical site to use for tactile displays because fingertips must not be impeded and their mobility makes them an inferior frame of reference for the motion of the entire body (relative to the abdomen). Ideally, tactors are required to be wearable (i.e., small and light), powerful (able to stimulate less-sensitive areas of the body), and have a wide frequency range (to take advantage of the skin's temporal capabilities). We identified such tactors and they are described further in the Methods section. This section describes the stimulus patterns we chose to test.

The repetition rate of discrete on/off "bursts" (rhythms) of vibration is an important issue , since this may offer an alternative time-related cue which has shown promise in the literature (van Erp, 2007) and may even be more effective than using vibratory frequency or amplitude, per se (Brown, Brewster, and Purchase, 2005; Swerdfeger et al., 2009). The advantage of a bursting on/off stimulus is partly derived from the fact that this will minimize sensory adaptation (Hahn, 1966; Hollins, Goble, and Delemos, 1991). A physical stimulus that remains constant for more than 200 to 300 milliseconds (ms) will gradually decrease in its perceived intensity. However, separate bursts repeating with noticeable "off" times (e.g., Van Doren, Gescheider, and Verrillo, 1990) will minimize this effect. Bursting, however, adds another technical challenge: the need for a rapid temporal response from the vibrotactor. Eccentric-mass or motor-type vibrators take a significant amount of time to "spin up" to maximum amplitude; moving-magnet linear actuators respond more rapidly to the driving signal. For this reason, we chose linear actuator-type tactors (http://www.eaiinfo.com/home.htm).

Scope of the present study

This first study will be limited in scope and will not attempt to include all potential aspects of tactile meaning in relation to looming. A rich literature has sprung up recently concerning the vast potential for tactile displays to convey specific meanings far beyond the primitive meanings conveyed in the past (e.g., a simple vibration alarm to indicate a phone call). Considerations have included: the optimal applications of passive, tactile, hands-free displays versus manual or manipulative (haptic) displays; the perceptions conveyed by different types of stimulus devices (electrotactile stimulators, linear vibrators, eccentric mass vibrators, hair-like styli); the perceptual effects (e.g., affordances, affective associations) triggered by changing stimulus variables (frequency, amplitude, duration, rhythm, spatial distribution); complex interactions among stimulus variables (e.g., frequency and amplitude interact to affect salience, just as they do in audition); and the potential for a formal lexicon of stimulus variables (e.g., distinguishability of abstract stimulus clusters for use in building a library of tactile icons versus building a set of metaphorical stimuli or exploiting tactile "melodies"). Moreover, numerous receptor types are embedded in the skin (e.g., in glabrous skin alone are found Ruffini, Meissner, Pacinian, and Merkel capsules, as well as free nerve endings, with analogous structures in hairy skin) (Bolanowski et al., 1994), accounting for a complex, non one-to-one mapping for at least seven distinct qualities of skin sensation (temperature, pain, pressure, stretch, vibration, itching, and stroking). To add further to the complexity of the situation, combinations of these aforementioned qualities account for even more perceptual experiences. For example, pressure and coolness can be perceived as wetness (Bentley, 1900). Clearly, numerous variables are potentially relevant to human perception of tactile stimuli and basic research on tactile perception can be quite complicated.

Our approach was to simplify the study of tactile meaning by focusing on a few of the more obvious and promising tactile looming stimuli in a limited set of circumstances that are roughly analogous to monaural audition. Our assumption was that a time- or intensity-varying vibration cue emanating from a localized body site can communicate the desired tactile concept/meaning (Brewster and Brown, 2004) of looming or approach. Our goal was to ensure that we chose an unambiguous stimulus *before* we attempted follow-up studies to quantify other, more complicated aspects of interception judgments (predicted heading, time-to-contact, spatial cues from multi-tactor flow fields, etc.).

While it is known that visual and auditory stimuli can convey looming; this study is intended to show that the meaning of looming can also be conveyed with tactile stimuli. Studies of this type contribute further evidence to build the library of percepts known to exist in visual and auditory modalities (such as spatial or temporal summation, adaptation and habituation, or contrast sensitivities) that also exist in the tactile modality. If this is the case with looming, it would imply a modality-neutral response consistent with a general underlying perceptual mechanism (Gordon and Rosenblum, 2005; Bicchi et al., 2008). The present study manipulates frequency and patterning of the vibrotactile stimulus in a way analogous to auditory cues to looming. The present study is intended to determine what can be conveyed by a simple, localized tactor stimulus and establish logistical and methodological issues of tactor experimentation, which will benefit the following study. Specifically, we wish to determine whether varying the quality of the vibrotactile stimulus during the pattern epoch at a local body site can be used to convey the concept of looming. We expect that subjects should be able to identify increasing tactile frequencies and/or beat frequencies as stimuli capable of conveying looming, just as analogous stimulus parameters (viz., perceived frequency) convey the looming of an approaching sound source.

Methods

Selection/protection of subjects

Subject population

All protocols were approved by the USAARL Institutional Review Board for the Protection of Human Subjects. The subjects (*N* = 35[3]) were active-duty or reserve military service members (17 of the 35 subject) or government employees (18) working at Fort Rucker and able to fit the protocol criteria (discussed below). The mean age of the subjects was 35 years (*SD* = 9.2). No race, ethnicity, or gender limitations were applied. There were 24 male and 11 female subjects.

Inclusion criteria

The study recruited healthy individuals of either sex, age 19 or older, in active duty or reserve status, and government employees. No otherwise-eligible legally-adult subjects were excluded from participation solely because of their age.

Exclusion criteria

Self-reports (via questionnaire) of skin injuries (e.g., open wounds), diagnosed diseases, special skin sensitivities, or numbness in the areas of the body where the vibrotactile stimulus was to be applied (e.g., due to severe hives, dermatitis, rashes, eczema, shingles, fibromyalgia, or severe sunburn) were criteria for exclusion. Although tactors were never applied directly to the skin, both for reasons of hygiene as well as to standardize the test conditions, these skin conditions might have rendered the vibrotactile stimulus uncomfortable, affecting a person's judgment of the vibrotactile pattern. A very minor wound, rash, or sunburn in a body site removed from the site of tactor placement was not considered exclusionary.

Injury/discomfort from vibration

The vibrations delivered to the subject were typical of those felt in routinely-used consumer devices such as pagers and cell phones and far below the suggested limits for human exposure (as described in standards and directives such as EU 2002/44/EC). The proposed particular types of tactors (manufactured by Engineering Acoustics, Inc. [EAI], of Castleberry, FL) have been used in several clinical studies (e.g., Goebel et al., 2009; Mortimer et al., 2011), as well as basic tactile research (e.g., Cholewiak and Beede, 2003; Cholewiak, Schwab, and Beede, 2003; Cholewiak, Brill, and Schwab, 2004). The stimulus was mechanical – no electricity passed from the tactor to the subject.

[3] A 36th volunteer did not meet the exclusion criteria due to a skin condition.

General equipment and procedures

Body sites for vibrotactile stimuli

Several body sites were considered during preliminary testing. Displays located on some sites (e.g., the fingers or hands) could be intrusive to the operator, while others (e.g., the feet or legs, as well as hands and arms) might lead to ambiguous percepts that depend on the limb position in three-dimensional space relative to the trunk of the body. For example, directional or letterform tactile stimuli (like p, q, b, and d) on the front or back of the hand can be “read” in different ways that depend on the orientation and position of the limb relative to the trunk of the body (e.g., Cho and Proctor, 2002; Shimojo et al., 1989).

Two body sites were chosen for formal testing: the abdomen and the forehead. The orientation of these two sites in space tends to be used to indicate to the operator where s/he is “pointed.” For example, Lewald and Ehrenstein (2000) have shown that changes in eye position and retinal eccentricity of a target can affect perceived direction as measured by hand pointing, but the perception of the direction in which the trunk of the body is pointing is not affected by any of these changes. Extensive clinical work by Karnath (1994) has shown the importance of coordinated peripheral sensory input to form an “egocentric body-centred (sic) coordinate frame of reference.” Asymmetric vibrotactile stimulation of sites such as the muscles of the neck could produce deviation in the perceived body orientation and the mental representation of the body’s position in space, based on the position of the abdomen. Of additional relevance are the findings of Cholewiak et al. (2004), who found that localization of brief vibrotactile stimuli (presented with a belt of 12 EAI C2 tactors) was virtually perfect at the midline of the abdomen, but fell to some 70 percent accuracy for sites to the side and under the arm.

However, in addition to the apparent usefulness of the abdomen as a candidate body site, it became clear during preliminary evaluations that when the forehead was stimulated with some vibrotactile patterns, between the eyes, a dramatic percept of an approaching stimulus was evoked. This experience was described by an experienced observer as “something coming right at my face.” Consequently, this site was added for further testing. There is some precedent for the usefulness of this site. Notable examples include Noiszewski's Elektroftalm, built in 1897, (described by Starkiewicz and Kuliszewski, 1963), that presented complex pictorial patterns to the forehead (see figure 1). Bliss, Katcher, Rogers, and Shepard (1970) later described the use of this site for two-dimensional tracking of moving targets. More recently, while testing sites for a tactile prosthesis to aid balance, Asseman, Bronstein, and Gresty (2005) report that stimulation of the forehead with 200-Hz vibration led to faster reaction times than when the same stimulus was presented to the sternum. Similarly, in a clinical study, Goebel et al. (2009) successfully used a head-mounted array of four EAI C2 tactors (one placed on the middle of the forehead) to provide balance cues for patients with bilateral vestibular loss. Finally, Mortimer et al. (2011) successfully presented spatiotemporal patterns across the forehead (using EAI C3 tactors) to assess perceptual changes resulting from sports-related concussion.

Figure 1. Noiszewski's Elektroftalm 1897.

Vibration was also applied to a third body site, the thumb and index finger of the left hand, in an auditory control condition. In this case, a larger vibrator (Labworks ET-132-203 electrodynamic minishaker) was used for reasons explained in the description of this condition (see below).

The tactors

Pilot studies explored several commercially-available tactors from EAI (http://www.atactech.com/PR_tactors.html), including their C2, C3, and EMR tactors (Redden et al., 2006; Brown et al., 2005; Schwab, 2008). The first two are moving-magnet, linear actuators small enough to be wearable at most body sites. The tactors are resonant in the frequency range of greatest human sensitivity on glabrous skin (i.e., 200 to 300 Hz), but can operate at lower frequencies. They have a peak displacement of about 1 mm, and an "on" response time of < 10 ms. The EAI EMR tactors are motor-based actuators that are about the same size but have a resonant frequency in the range of 50 to 140 Hz, with a peak displacement of about 1.2 mm (www.atactech.com/PR_tactors.html). Pilot work led to the choice of the EAI C3 tactors for this study. They are relatively small (19 mm diameter, 6 mm thick), light (< 17 gm), bio-isolated, and provided with suitable software for the design of the needed stimulus patterns.

Stimulus control

Stimulus patterns were generated under computer control using software and a tactor control interface, designed and sold by EAI. The software allowed moment-by-moment programming of the pattern of vibrations by defining sequences of bursts of vibration with specific durations, vibratory frequencies, and physical intensities. Duration had a resolution of 10 ms while frequency could be specified to 1 Hz. Intensities could be defined in the software in four voltage steps, but because we had no measure of the relative physical displacement of these four levels, we always used the maximum available intensity. Defining all of these parameters at a zero level effectively produced a quiet "interburst" interval. Each of our looming patterns were sequences of 20 bursts of vibration separated by inactive interburst intervals, with the total pattern lasting about 3 seconds (s). Depending on the test condition, vibratory frequency, burst duration and/or interburst interval duration would consecutively increase or decrease over the course of the 3-s pattern. In control conditions, the levels would either be constant or varied randomly over the 20 bursts of vibration.

Stimulus generation

To increase the salience of the tactile stimulus, vibrotactile stimuli were generated with two adjacent EAI C3 tactors at each body site. The use of a stronger stimulus produced by the two tactors (through spatial summation, e.g., Goble, Collins, and Cholewiak, 1996), was meant to ensure that if subjects report that the vibratory stimulus is not consistent with a display conveying looming, this negative finding would *not* be confounded by a basement effect, i.e., a simple failure on our part to provide a strong enough stimulus in the first place. Tactors were held against the body of the participant using a Velcro strap and/or small lengths of athletic tape (depending on the body site), to prevent it from moving during the study.

Auditory masking noise

A unique auditory masking stimulus was employed to attenuate unwanted sounds, particularly for the head-mounted tactors. This concern for sound dampening/masking was deemed necessary because, unless masked, unwanted air- and bone-conducted noise from the vibrating tactor can readily produce a confounding auditory cue (e.g., Hood, 1962; McBride, Letowski, and Tran, 2005). The authors determined that the best way to ensure that the qualities of the tactile stimuli could be judged without auditory confound was with a combination of "pink" masking noise mixed with the sound of a randomly-occurring tactor vibration stimulus. The noise was developed in collaboration with colleagues at EAI and in the Acoustics Branch of USAARL. This complex noise was played directly through commonly-used military communications earplugs (CEP). These improve the delivery of the masking noise and passive dampening of sounds emanating from the vibrating tactors. It was found that the ear plugs produce less bone-conducted sound than ear muffs (which tended to form an unwanted sound chamber over the skull when the tactor was vibrating on the face).

Stimulus trial sequence

A stimulus pattern consisted of a train of 20 vibratory bursts. The minimum duration of any individual burst of vibration was 30 ms, while the duration of the interburst intervals was at least 20 ms. The total duration of the train of 20 bursts lasted approximately 3 s. The pulsating pattern was intended to minimize the potential confounding effects of vibrotactile adaptation that were described in the Introduction.

Six conditions were defined by the changes in either the frequency or the duration of the individual vibratory bursts within the pattern. These included: 1A) constant frequency (control condition); 1B) random frequencies (control condition); 2A) decreasing frequency (from high to low); 2B) increasing frequency (from low to high); 3A) decreasing beat speed (decreasing the rate of bursts by increasing the on/off durations – another way to vary apparent vibration frequency); 3B) increasing beat speed (increasing the rate of bursts by decreasing the on/off durations). The ranges of frequencies and durations over the 20 bursts for each condition are shown in table 1.

Table 1.
Ranges of burst frequency and duration for each condition.

Condition	Frequency (Hz)		Duration (ms)	
	Start	End	Start	End
1A	250	250	30	30
1B	random 30-250	random 30-250	30	30
2A	250	30	30	30
2B	30	250	30	30
3A	250	250	300	30
3B	250	250	30	300

These conditions were presented to the forehead (labeled 1a to 3b in table 2) and the abdomen (equivalent conditions labeled 4a to 6b). The conditions were also presented acoustically (labeled 7a to 9b) in an auditory control block of trials. This control was deemed necessary to include because the high level of noise needed to mask any bone conduction in the forehead condition may have produced cognitive distraction that could have influenced the observer's judgments. In this auditory confound control block of trials, the subject listened to the sound of the vibrating tactor playing in front of, but not touching, the face. Simultaneously, subjects felt a random tactile stimulus on a remote site (the fingertip). This random stimulus was identical to the special masking noise that was played through the earphone in the vibrotactile test blocks, described above. Because of the wide dynamic range of the stimulus, a separate type of vibrator was used (Labworks ET-132-203 electrodynamic minishaker). Since judgments of tactile patterns in the other trial blocks were made in the presence of irrelevant random auditory noise, this control has subjects making judgments of auditory stimuli in the presence of irrelevant random tactile noise. The subject provided all the usual ratings (to be described below) of the *sound* of the tactile stimuli presented in the other test blocks, but in the absence of concomitant tactile cues. The intention was that this control would allow better interpretation of the main experiment findings concerning the isolated tactile effects of the vibration stimuli. Subjects were tested in blocks of trials with the vibrotactile conditions on the forehead, the vibrotactile conditions on the abdomen, and with the auditory control condition, with order of presentation of these three balanced over individuals (shown in table 2):

Table 2.
The eighteen experimental conditions.

A. Tactile: Forehead	1A Constant Control	1B Random Control	2A Decreasing Freq.	2B Increasing Freq.	3A Decreasing Beat	3B Increasing Beat
B. Tactile: Abdomen	4A Constant Control	4B Random Control	5A Decreasing Freq.	5B Increasing Freq.	6A Decreasing Beat	6B Increasing Beat
C. Auditory	7A Constant Control	7B Random Control	8A Decreasing Freq.	8B Increasing Freq.	9A Decreasing Beat	9B Increasing Beat

In a repeated-measures design, each subject was presented with each of the conditions in a paired-comparison protocol, with order of presentation balanced among subjects. A trial, vibrotactile or acoustic, consisted of a pair of patterns in which the two stimuli were compared. Using the designations in the Tactile Forehead cells in table 2, a trial was made up of either pair #1, pair #2, or pair #3, with the order of the a to b members randomized over trials. So Trial 1 might have consisted of 3b followed by 3a, trial 2 might have consisted of 2a followed by 2b, and so on. In this manner, six possible pattern pairs were constructed: 1a1b, 1b1a, 2a2b, 2b2a, 3a3b, and 3b3a. Similar pairings were constructed for the Tactile Abdomen and Auditory series. In a block of trials, each pair was repeated twice for a total of 12 trials per block. Furthermore, the observer received three exposures of the pair, separated by 10 s, before a judgment was required. Repetition of stimuli in this manner is common in the psychophysical literature (e.g., Collins and Cholewiak, 1994), allowing subjects a sufficient number of exposures to be confident of their judgments without presenting so many repetitions as to cause undue fatigue or boredom.

Dependent measures and test procedure

Dependent variables

Subjects were required to identify which pattern in the pair best conveyed the impression of looming and then provide several verbal ratings of that pattern. Finally, after all 12 pairings were judged, subjects generated a retrospective verbal rank-ordering of the 2 top-rated pairs. These main measures are described below. As an additional source of possibly useful information, subjects were asked to rate the confidence they had in their retrospective rank-ordering, from 1 = “not confident at all” to 7 = “completely confident.” Likert-type 1 to 7 ratings are often used to rate qualities of stimuli in psychophysical and social studies. However, our experience during the pilot tests indicated that this Likert approach created a potential ambiguity. Stimuli which were rated very low for looming (generating a judgment of 1) may have been rated low either because the stimuli were perceived as stationary or because they were perceived as moving away from the subject. Consequently, two different perceptual entities could lead to the same numerical rating. This problem was avoided by a modification of the typical instructions concerning a 1 to 7 scale, i.e., by using semantic opposites at the ends (transforming the scale into a semantic differential scaling; e.g., Osgood, Suci, and Tannenbaum, 1957).

1. <u>Semantic differential</u>: "Rate what the stimulus felt like on the continuum below." (1 = "like a real object moving away from me;" 7 = "like a real object moving towards me"):
   1   2   3   4   5   6   7

An attempt was made to avoid the use of terms such as salience or looming when communicating with subjects concerning their ratings. Rather, based on discussion amongst the investigators and past semantic differential work in the literature (e.g., Heise, 1965), instead of saying "looming," we emphasized simpler and more common words/phrases that had fewer possible meanings and would be better understood by subjects, such as "moving towards (me)" or (its opposite) "moving away (from me)." Similarly, instead of saying "salience/salient" as used in the pilot study, we substituted "weak" versus "strong" (overall stimulus salience) or "decreasing" versus "increasing" (stimulus salience over time during a given vibration trial). The specific scales are defined below. This improvement and diversification of the terms to be used in the rating scales should aid interpretation of the looming data. For example, if a significant correlation is obtained between looming and "increasing," but not between looming and the other variables (such as "strong"), this would imply that "increasing" may be a more important stimulus quality for conveying looming.

<u>Ratings</u>

Subjects were asked to provide semantic differential ratings on a 1 to 7 scale of the "best" stimulus in terms of how well the concept of looming was conveyed, with 1 = the stimulus was "like a real object moving away from me" and 7 = the stimulus was "like a real object moving towards me." The ratings were perceptually anchored before the study by exposing the subjects to an actual example of a looming auditory stimulus. The reference stimulus consisted of a noisy battery-driven toy truck that traveled directly towards (or away from) the seated subject's body for the same amount of time as our vibration stimuli. When traveling towards the subject, it also collided gently with his/her chest. When traveling away from the subject, it started in contact with his/her chest. The experience of approach and gentle collision was defined as a 7 (because it constituted real looming with full fidelity auditory and tactile cues). Conversely, listening to the toy vehicle move away from a starting position touching the subject was deemed a 1. Listening to the vehicle operate in place at a fixed distance in the middle of its travel was called a middle rating of 4 (because there is vehicle noise in the absence of any meaningful cues concerning looming). The data concerning the stimulus conditions were used to establish how close each stimulus came to the optimal display for conveying looming, which is a real object approaching one's body with the possibility for a collision.

In addition, certain other ratings based on the "saliency" dimension were solicited, which may aid interpretation of the looming ratings. Subjects were asked how salient they found the stimulus in order to confirm that all subjects found the stimuli detectable and to determine if a correlation existed between the perceived strength of the stimulus and how well it conveyed looming. Thus, a 1 to 7 rating of "strength" of the stimulus was requested (weak vs. strong: 1 = "not at all detectable", 7 = "very detectable, can't be missed"). This question allowed us to determine if a negative looming result would merely be due to a basement effect for saliency. The need to determine if subjects could perceive whether the stimulus in some way increases or decreases is necessary, regardless of whether they feel that this change conveys looming. For this reason, a 1 to 7 rating was requested where 1 = "definitely decreasing" and 7 = "definitely increasing". This allowed us to explore the extent to which "looming" and "increase" were correlated entities. Finally, we explored whether subjects perceived any useful warning qualities of the stimuli, regardless of whether they conveyed looming. Thus, a 1 to 7 rating was requested where 1 = "stimulus conveys a safe condition" and 7 = "stimulus conveys a dangerous condition". In summary, four ratings were generated for each trial: Looming: (Moving Away…Moving Towards), Salience: (Weak…Strong), Salience: (Decreasing…Increasing), and Salience: (Safe…Dangerous).

Rank-orderings

In addition, subjects were asked retrospectively to provide a separate comparison of their three top-rated stimuli, such that first place be given to the most convincing display for conveying looming and second place be given to the least convincing. This ranking was done to more clearly detect any relative differences among the stimuli, i.e., to answer the question: "Which of the patterns is best?" (regardless of whether any of them were optimal). Subjects were able to see all their prior ratings when they made the final rank-ordering decision, but were not required to be consistent with those ratings.

Session protocol

Subjects were briefed verbally by an experimenter before reading the consent form and deciding if they wished to volunteer. After reading and signing the Informed Consent, the subject then completed the medical status review of skin conditions, and if no exclusionary conditions existed, was taken to the test area. Depending on the random order of test conditions chosen for the particular observer, the tactors were fitted to the person's forehead, fitted to their torso, or placed in front of the face using a special suspension mount. The tactors were held against the body of the subject comfortably, using a Velcro strap and/or easy-release athletic tape (for the torso and head, respectively), which prevented the tactors from slipping during the study. The subjects then put in the military communications earplugs that transmitted the special masking noise intended to minimize distracting acoustic cues from the tactors and from environmental events.

The experiment session consisted of exposing the subject to the familiarizing stimulus (the actual looming remote control vehicle), then progressing through the series of conditions of vibratory and auditory stimuli, and asking for perceptual judgments. A rest of at least 10 s was provided between each of the 12 trials within a block, to minimize the potential confounding effects of habituation and allowing adequate time for the subject to provide ratings. Perceptual judgments, as well as retrospective rankings of the top-rated stimuli, were elicited from the subject and recorded by the experimenter.

Additionally, after all rating and ranking data were obtained and the experiment was concluding, subjects were asked an open-ended question, namely, if they could think of any other meanings conveyed by the stimuli they just experienced. It is conceivable that subjects might have identified an increase in frequency as being capable of conveying a tacton we did not study. This was done to inform readers about other possible uses of the vibrotactile cue. Such information may be found useful for future experiments intended to exploit tactile displays in new ways.

Procedures in the Auditory control conditions were identical to those described above, with the following exceptions: 1) The tactors did not touch the subject's body but were located on a stand in front of the subject, who rated the sound of the tactor vibration. 2) The subjects were asked to attempt to make this rating in the presence of distractor stimuli analogous to those in the tactile conditions, namely, the subject touched a vibratory stimulus (with his/her finger) that was driven by the same pink noise/random vibrator signal as used in the tactile conditions.

Results

Looming

Looming ratings

Table 3 displays the mean looming ratings obtained for every condition. A two-way repeated-measures Analysis of variance (ANOVA) (3 by 6) was conducted to assess the effects of site of administration of the stimulus (site [with three levels: head, abdomen, auditory]) and stimulus pattern (stimulus [with six levels: non-varying control, randomly varying control, decreasing frequency, increasing frequency, decreasing beat speed, increasing beat speed]) on looming ratings. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the main effect test of site, $\chi^2(2) = 2.75$, $p = .256$. There was no significant main effect of site on looming ratings, $F(2, 68) = .755$, $p = .47$, *partial* $\eta^2 = .02$. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect test of stimulus, $\chi^2(14) = 41.19$, $p < .001$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .736$). There was a significant main effect of stimulus on looming ratings, $F(3.68, 125.18) = 165.67$, $p < .001$, *partial* $\eta^2 = .83$. Mauchly's test indicated that the assumption of sphericity had been violated for the test of an interaction between site and stimulus, $\chi^2(54) = 108.55$, $p < .001$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .639$). There was a significant interaction effect for site and stimulus, $F(6.39, 217.12) = 5.06$, $p < .001$, *partial* $\eta^2 = .13$. This interaction implies that even though there was no main effect for site (and the main effect for stimulus was quite strong), the effect of stimulus still varies somewhat at different sites. For example, it can be seen in figure 2 that when decreasing beat speed was presented via an auditory stimulus, the mean rating (5.17) trended slightly higher (n.s.) than the mean rating (4.09) when increasing beat was presented auditorily, whereas the opposite trend was obtained (increasing beat speed trending higher than decreasing) for every tactile condition.

Table 3.
Mean looming ratings.

Conditions and groups	*N*	*M*	*SD*
Condition 1A, fixed constant average			
Head (1a)	35	4.33	1.01
Abdomen (4a)	35	4.37	0.84
Auditory (7a)	35	4.44	0.68
Condition 1B, random constant average			
Head (1b)	35	4.43	0.71
Abdomen (4b)	35	4.23	0.77
Auditory (7b)	35	4.06	0.53
Condition 2A, decreasing frequency average			
Head (2a)	35	1.99	0.89
Abdomen (5a)	35	2.26	1.16
Auditory (8a)	35	1.81	0.78
Condition 2B, increasing frequency average			
Head (2b)	35	6.07	1.05
Abdomen (5b)	35	6.49	0.62
Auditory (8b)	35	6.33	0.67
Condition 3A, decreasing beat speed average			
Head (3a)	35	4.43	1.16
Abdomen (6a)	35	4.20	1.12
Auditory (9a)	35	5.17	1.15
Condition 3B, increasing beat speed average			
Head (3b)	35	4.53	0.94
Abdomen (6b)	35	4.77	1.00
Auditory (9b)	35	4.09	1.09

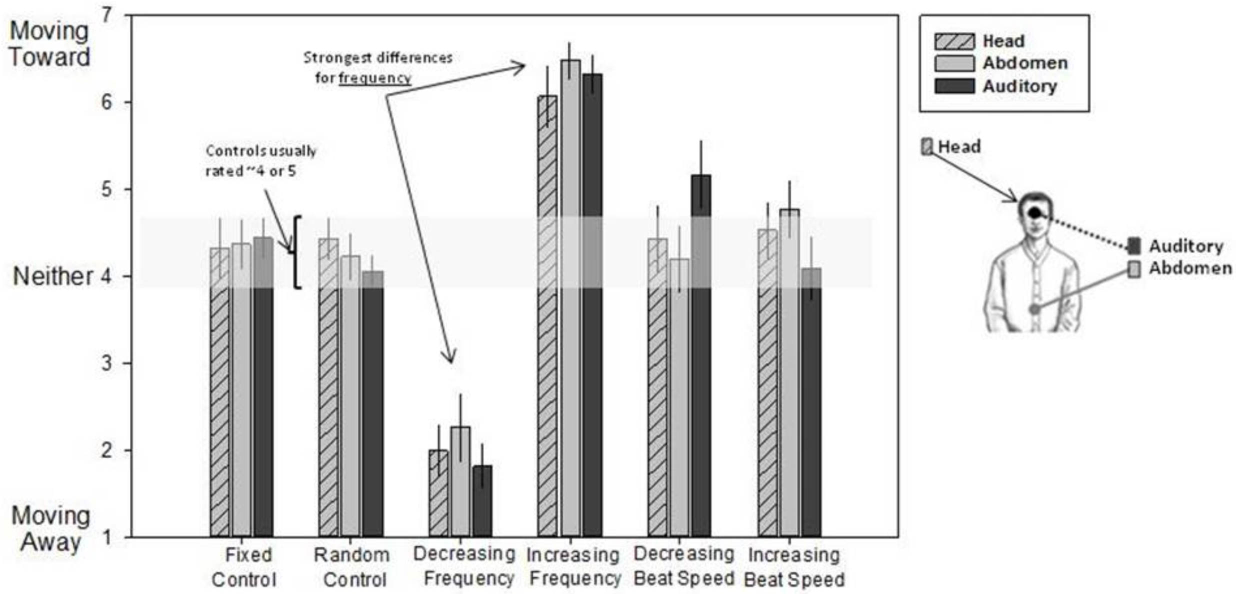

Figure 2. Looming ratings for different vibration patterns.

Figure 2 shows the looming ratings when subjects judged the six vibration patterns employed in this study. The figure shows the mean ratings (and confidence intervals) for the two control patterns (no coherent, monotonic change in vibration via either a constant frequency and duration of vibration pulses or a randomly changing frequency and duration of vibration) and the four treatment patterns (monotonic change in vibration via either decreasing frequency, increasing frequency, decreasing beat speed, or increasing beat speed). Mean ratings and confidence intervals are shown for tactile stimulation of the forehead between the eyes (“Head”) and for the torso near the solar plexus (“Abdomen”), as well as for an auditory comparison condition (hearing the same vibrations). The figure also shows that the highest scoring condition was “increasing frequency,” whereas the lowest scoring condition was “decreasing frequency.” These two frequency conditions were interpreted differently from all other stimulus patterns (Bonferroni-adjusted pairwise comparisons, $p < 0.01$). No other stimulus patterns were different from any others after adjustment for multiple comparisons. This implies that frequency was a better aspect of the vibration stimulus to manipulate than any of the other conditions when the purpose is to convey the concept of an object moving towards or away from the observer.

Looming rankings

When subjects were asked which vibration pattern they ranked as their first choice for conveying something looming towards them, the increasing frequency condition was chosen by the majority of the subjects regardless of whether the method of administration was tactile (head, abdomen) or auditory (see figure 3).

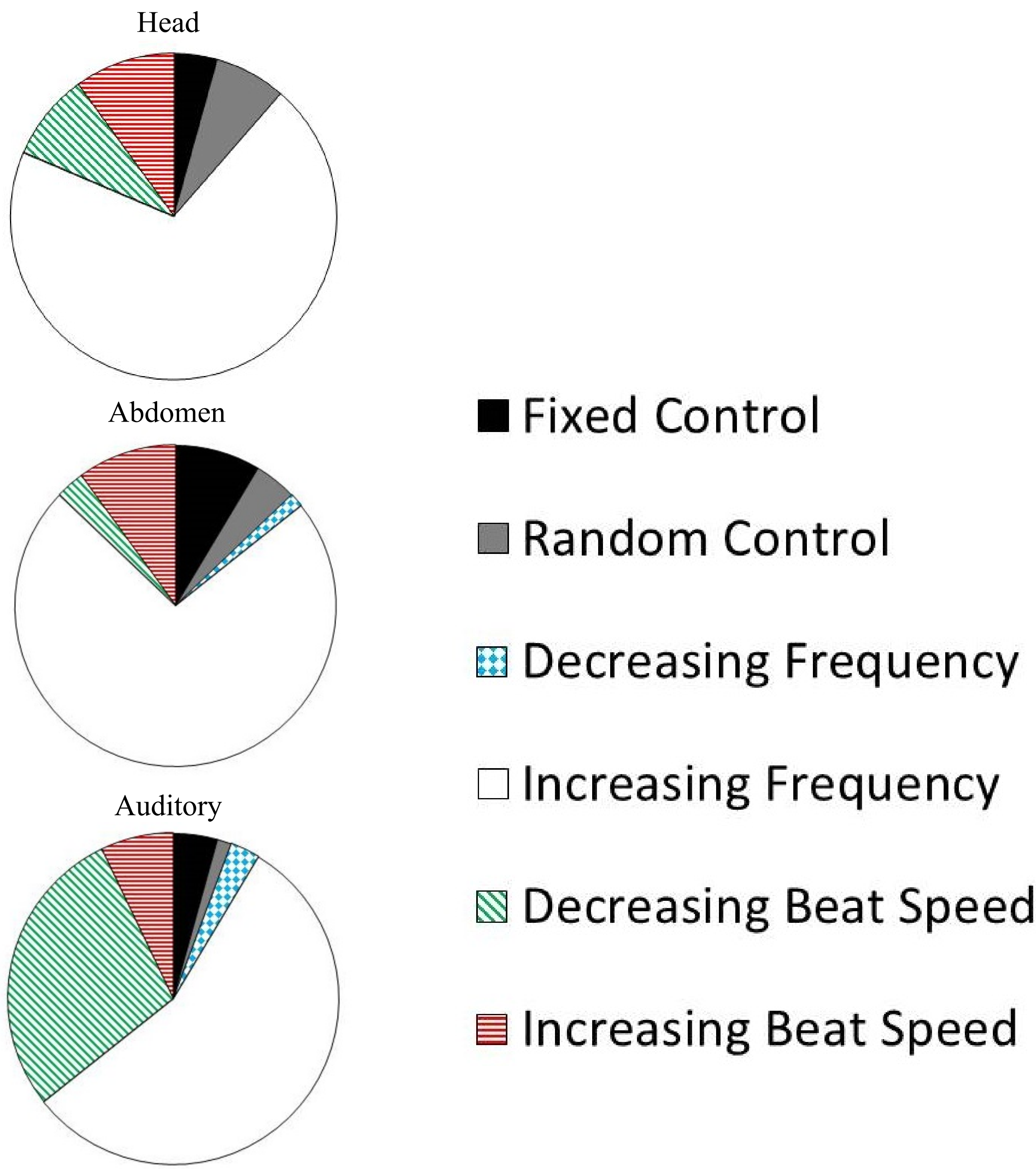

Figure 3. Preferred looming stimulus among three types of administration.

Other ratings

Ratings of each stimulus were also solicited for the semantic differentials "decreasing/increasing," "weak/strong," and "safe/dangerous," the statistics of which are discussed respectively here.

Decreasing/increasing

A two-way repeated-measures ANOVA (3 by 6) was conducted to assess the effects of site of administration of the stimulus and stimulus pattern on decreasing/increasing ratings. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the main effect test of site, $\chi^2(2) = 1.25$, $p = .535$. There was no significant main effect of site on decreasing/increasing ratings, $F(2, 68) = 1.81$, $p = .17$, *partial* $\eta^2 = .05$. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect test of stimulus, $\chi^2(14) = 40.75$, $p < .001$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .702$). There was a significant main effect of stimulus on decreasing/increasing ratings, $F(3.51, 119.29) = 168.92$, $p < .001$, *partial* $\eta^2 = .83$. Mauchly's test indicated that the assumption of sphericity had been violated for the test of an interaction between site and stimulus, $\chi^2(54) = 123.83$, $p < .001$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .500$). There was a significant interaction effect for site and stimulus, $F(5, 170.09) = 5.83$, $p < .001$, *partial* $\eta^2 = .15$. As can be seen in figure 4, the pattern of findings for decreasing/increasing is the same as was obtained for the looming ("going away/coming towards") ratings, implying that the perception of a monotonic decrease or increase in a vibration signal is associated with looming. This association was corroborated by the observation of significant positive correlation between looming (going away/coming towards) ratings and decreasing/increasing ratings (see table 4).

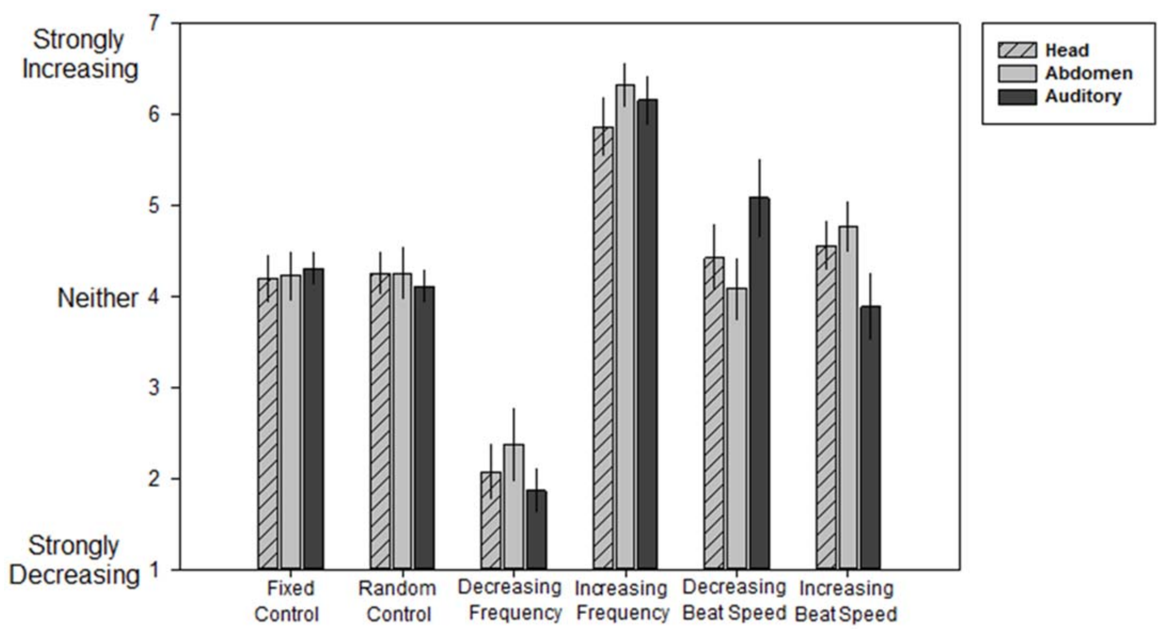

Figure 4. Decreasing/increasing ratings for different vibration patterns.

Table 4.
Correlations between looming and decreasing/increasing ratings for each condition.

Conditions and groups	Looming ($\overline{x}$)	Decreasing/increasing ($\overline{x}$)	Correlation (r)
Condition 1A, fixed constant			
Head (1a)	4.33	4.20	0.84
Abdomen (4a)	4.37	4.23	0.68
Auditory (7a)	4.44	4.31	0.76
Condition 1B, random constant			
Head (1b)	4.43	4.26	0.90
Abdomen (4b)	4.23	4.26	0.67
Auditory (7b)	4.06	4.11	0.60
Condition 2A, decreasing frequency			
Head (2a)	1.99	2.07	0.64
Abdomen (5a)	2.26	2.37	0.59
Auditory (8a)	1.81	1.87	0.73
Condition 2B, increasing frequency			
Head (2b)	6.07	5.87	0.79
Abdomen (5b)	6.49	6.33	0.52
Auditory (8b)	6.33	6.16	0.84
Condition 3A, decreasing beat speed			
Head (3a)	4.43	4.43	0.88
Abdomen (6a)	4.20	4.09	0.68
Auditory (9a)	5.17	5.09	0.69
Condition 3B, increasing beat speed			
Head (3b)	4.53	4.56	0.83
Abdomen (6b)	4.77	4.77	0.62
Auditory (9b)	4.09	3.89	0.70

Note: All correlations were significant at the 0.01 level of significance (2-tailed).

Weak/strong

Ratings of the “weak/strong” semantic differential are displayed in figure 5. A two-way repeated-measures ANOVA (3 by 6) was conducted to assess the effects of site of administration of the stimulus and stimulus pattern on weak/strong ratings. Mauchly’s test of sphericity indicated that the assumption of sphericity had not been violated for the main effect test of site, $\chi^2(2) = 1.52$, $p = .47$. There was a significant main effect of site on weak/strong ratings, $F(2, 68) = 7.50$, $p = .001$, *partial* $\eta^2 = .18$. Mauchly’s test indicated that the assumption of sphericity had been violated for the main effect test of stimulus, $\chi^2(14) = 78.04$, $p < .001$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .537$). There was a significant main effect of stimulus on weak/strong ratings, $F(2.68, 91.24) = 25.88$, $p < .001$, *partial* η^2 = .43. Mauchly's test indicated that the assumption of sphericity had been violated for the test of an interaction between site and stimulus, $\chi^2(54) = 87.93$, $p = .003$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .634$). There was a significant interaction effect for site and stimulus, $F(6.34, 215.44) = 5.87$, $p < .001$, *partial* η^2 = .14. The significant interaction implies that the effect of stimulus varies at different sites. As can be seen in figure 5, the only condition with a mean frating less than 4 was the random control pattern presented via an auditory stimulus. These results imply that all six vibration patterns used in this experiment were easily detected by the subjects.

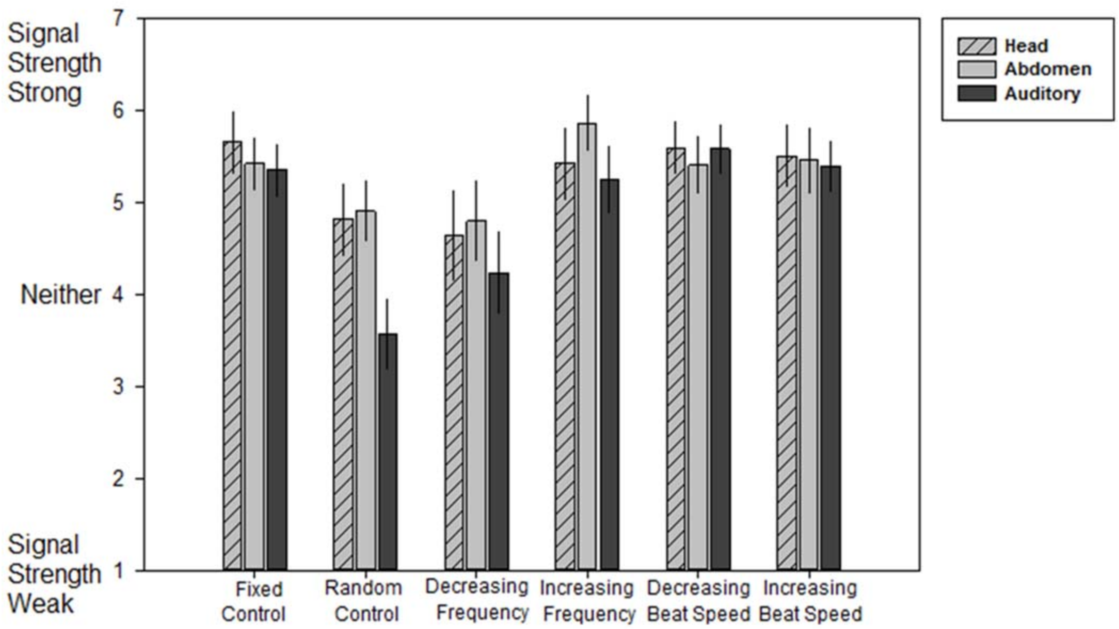

Figure 5. Weak/strong ratings for different vibration patterns.

Safe/dangerous

Ratings of the "safe/dangerous" semantic differential are displayed in figure 6. A two-way repeated-measures ANOVA (3 by 6) was conducted to assess the effects of site of administration of the stimulus and stimulus pattern on safe/dangerous ratings. Mauchly's test of sphericity indicated that the assumption of sphericity had not been violated for the main effect test of site, $\chi^2(2) = 1.33$, $p = .515$. There was no significant main effect of site on safe/dangerous ratings, $F(2, 68) = .327$, $p = .72$, *partial* η^2 = .01. Mauchly's test indicated that the assumption of sphericity had been violated for the main effect test of stimulus, $\chi^2(14) = 34.52$, $p = .002$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .730$). There was a significant main effect of stimulus on safe/dangerous ratings, $F(3.65, 124.15) = 55.88$, $p < .001$, *partial* η^2 = .62. Mauchly's test indicated that the assumption of sphericity had been violated for the test of an interaction between site and stimulus, $\chi^2(54) = 80.87$, $p = .012$, therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon = .693$). There was a significant interaction effect for site and stimulus, $F(6.95, 235.50) = 4.39$, $p < .001$, *partial* η^2 = .11. The same pattern of results was found for safe/dangerous ratings and looming ratings. These results imply that there is a positive association between looming (going away/coming towards) ratings versus safe/dangerous ratings, with a stimulus that is rated as approaching being also rated as more consistent with a dangerous condition.

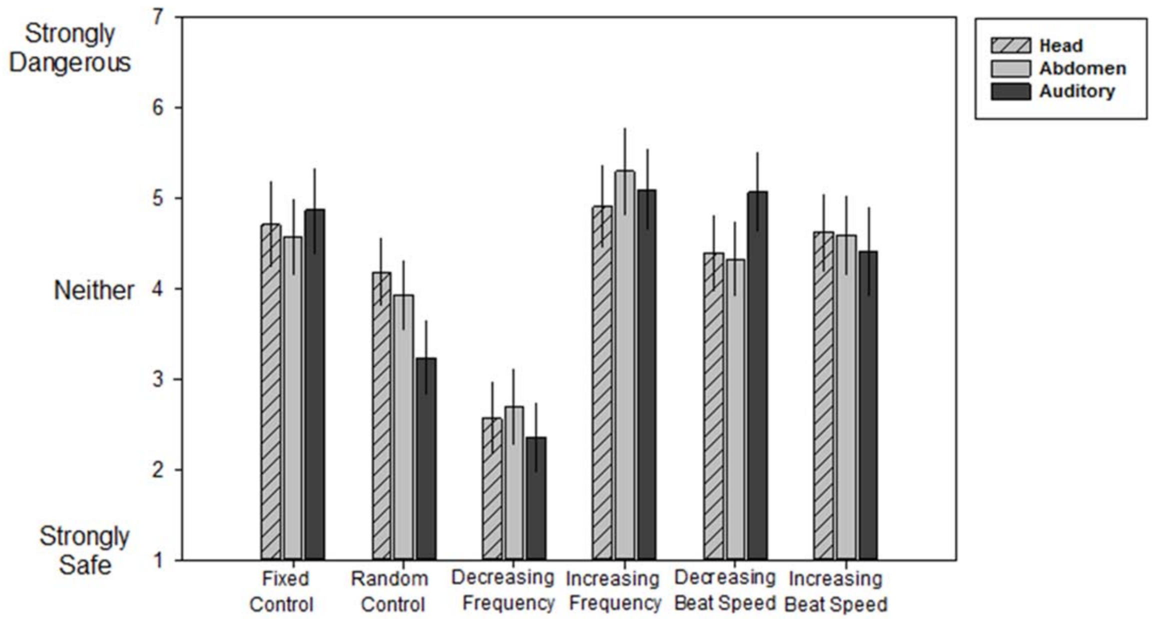

Figure 6. Safe/dangerous ratings for different vibration patterns.

After all rating and ranking data were obtained, subjects were asked an open-ended question, namely, if they could think of any other meanings which could have been conveyed by the stimuli they just experienced. For example, it is conceivable that subjects might have identified an increase in frequency as being capable of conveying intuitively the meaning of “rising” (such as rising in elevation). Such qualitative, post-hoc, exploratory descriptors were not part of the formal dependent measures analyzed by this study, but will be summarized in this paper because it may prove useful for future experiments intended to exploit tactile displays in new ways.

Discussion

The various tactile and auditory stimuli were easily detected and judged with confidence by the subjects. The main finding of this experiment is that it is possible to convey the concept of looming using a simple, localized tactile vibration cue. The findings are consistent with past research concerning the perception of looming via non-tactile sensory modalities (vision, audition), implying that the looming percept is generated by a modality-neutral mechanism (Gordon and Rosenblum, 2005; Graziano and Cooke, 2006; Bicchi et al., 2008).

The looming tacton (Brewster and Brown, 2004) was conveyed most clearly by systematically varying the frequency of the tactile stimulus. Increasing frequency (from low to high) of vibration over time was found to be consistent with a stimulus moving towards that participant, while decreasing frequency was consistent with a stimulus moving away from the participant. This contrasting result ("towards" versus "away") for the same stimulus quality (frequency change) lends more validity to the findings than if we had only found that an increasing frequency stimulus conveyed the approach of an object towards the subject. We hypothesize that the frequency cue worked best because the increase in vibration saliency and frequency it delivers over time is roughly analogous to a natural auditory cue. As the frequency of the vibration stimulus increased over the stimulus period, the effect may be analogous to the perceived increase in pitch of an approaching sound source. Moreover, the vibration stimulus should increase in detectability over the stimulus period as it approaches the more salient higher frequency (Gescheider, Capraro, Frisina, Hamer, and Verrillo, 1978), which may emulate the perceived increase in loudness of an approaching sound.

It is logical to conclude that the frequency cue worked to convey the looming tacton. The frequency cue was the closest analogue in this experiment to the natural Doppler shift, which is important to auditory perception of looming. This interesting similarity merits further investigation.

In many past tactile applications, varying the beat speed of tactile pulses has been exploited to convey changes in closing distance of targets or obstacles. The current study implies that varying frequency of vibration may be a more ecologically-valid tactile cue for looming than varying beat speed. One of the reasons beat speed has been used in the past is that the frequency of vibration can be held at the highly salient frequencies around 250 Hz, thus avoiding the use of lower frequencies, which are not as salient. However, as tactor technology continues to improve and salient stimuli can be produced in wider frequency ranges, frequency will become an important source of tactile cueing even outside of highly-controlled laboratory conditions.

No main effect was found (in semantic differential ratings) concerning the site of administration of the stimulus (head versus torso versus auditory). Nevertheless, in more focused and sensitive comparisons of the stimuli, a difference was indicated, i.e., 71.4 percent of subjects preferred the head (over the torso) for conveying approach (see figure 7) when asked to make a forced choice between these two tactile conditions. This is scientifically interesting, because head and torso collisions both represent important threats to an organism, but the head is a more vulnerable region of the body and collisions to the head should trigger a stronger aversive reaction. The head has not been used much in past tactile cueing research concerning spatial orientation in flight, but head-based cues may be appropriate for certain applications. The main weakness of basing a looming display on the head is that the head is mobile on the body, whereas the torso is more of a stable frame-of-reference concerning one's own movements through the world. Nevertheless, when there is a need to ensure the warning does not get ignored, the head may serve as an additional site for cueing. For example, if an initial torso warning does not cause a control input within a certain amount of time, then warnings on both the head and torso could be activated that are consistent with the external location of the threat.

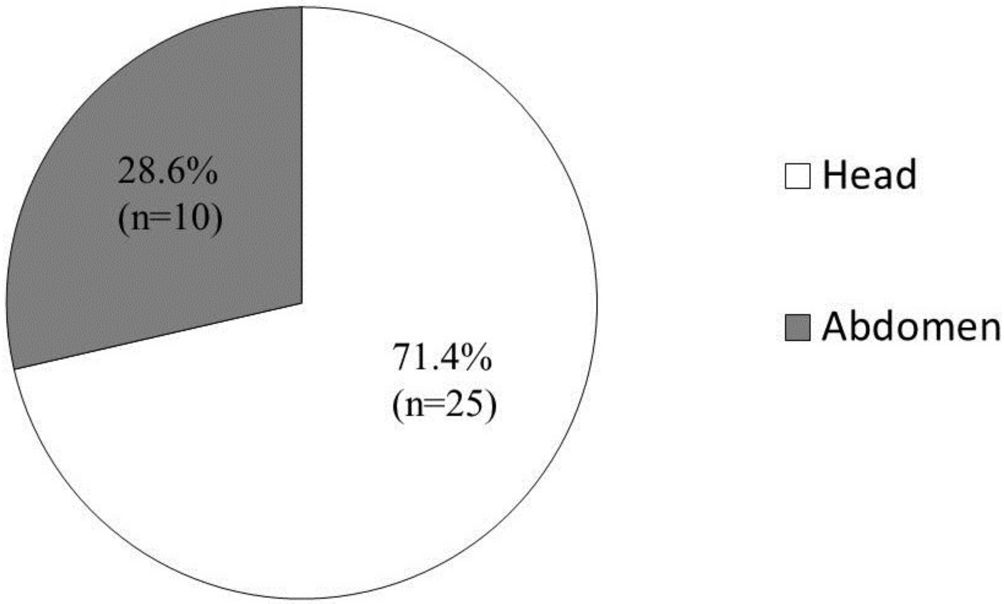

Figure 7. Preferred tactile site for conveying approach.

We have attempted to rule out two potential confounds to the interpretation of our findings regarding increasing and decreasing vibration frequency, as discussed below:

1) It not likely that our finding that varying frequency of vibration was the best-performing looming tacton can merely be attributed to our frequency conditions being more salient stimuli, since both of the beat speed (decreasing and increasing) conditions and one of the control conditions (non-varying vibration) vibrated at 250 Hz, which is known to be a more salient frequency than the majority of the frequencies used in the frequency condition. Moreover, when subjects rated the strength of the various stimuli (apart from whether they conveyed looming), their ratings indicated that the frequency condition was not a stronger stimulus overall versus the conditions. Therefore, it is likely that other properties of the frequency stimulus were important, such as the inherent meaning of varying frequency as a looming tacton. On a related point, it is not likely that the other (non-frequency) conditions simply failed to be sufficiently salient or were confusing, because the mean ratings for stimulus strength did not imply a basement effect for any of the conditions (figure 5) Also, after the experiment, the subjects expressed high global confidence in their ratings (5.77 ± 0.589, [where 1 = "not confident at all" and 7 = "very confident"]). For these reasons, we infer that our frequency conditions represent viable looming tactons.
2) While humans are most sensitive to varying (versus unchanging) stimuli, our findings concerning the usefulness of the vibration frequency as a looming tacton cannot be attributed entirely to the frequency condition merely having been more variable over time than the other conditions of our study. This is because the random control condition was the most variable condition of all, yet it did not perform well as a looming tacton. The fact that neither of the tactile control conditions performed as well as the tactile frequency condition implies that conveying looming in the most intuitive manner requires more than

simply conveying a salient but nonspecific alerting signal. We infer that the specific and intuitive tactons being conveyed by our frequency conditions were the concepts "approaching" and "receding."

Our study found strong evidence that rising vibration frequency is a viable candidate tacton for conveying approaching or looming, while falling frequency is a viable candidate tacton for conveying receding. Nevertheless, it is possible that during open-ended questioning, subjects may be able to think of additional tactons consistent with a rising or falling vibration frequency stimulus. For this reason, after all rating and ranking data were obtained, subjects were asked if they could think of any other meanings which could have been conveyed by the stimuli they just experienced. These findings are presented in figure 8; they reveal that the majority of subjects did not agree on any single alternative descriptor. Also, many subjects (10 of 25 participants) could not come up with any additional descriptors besides approaching/receding (i.e., the best-rated looming descriptor). Nevertheless, some subjects felt that the vibration stimulus could be exploited to convey other concepts as well, such as a change in speed (mentioned by 8 participants) or a change in altitude (mentioned by 6 participants).[4] In summary, while there was no overwhelmingly favored concept besides looming; there were a number of additional or alternative applications of the stimulus mentioned by a minority of subjects. One of these, changed altitude, is particularly interesting. This is because we have separately developed a prototype seat display for potential future testing of looming perceptions (Lawson, Cholewiak, Brill, Rupert, and Thompson, in submission) and it is logical to suppose that a vibration stimulus in the seat that is meant to convey looming (towards the Earth) could prove very useful indeed if it also happens to connote decreasing altitude.

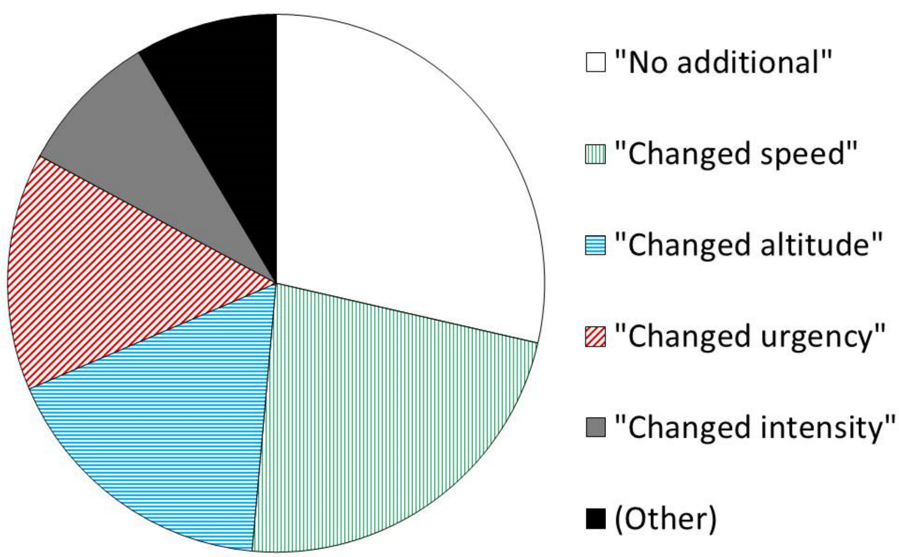

Figure 8. Additional concepts besides changed distance (looming) that subjects thought might be conveyed by the changing vibration frequency stimulus.

[4] A few subjects noted that the changing vibration frequency stimulus could also be utilized to convey a change in urgency (5 participants) or intensity (3 participants), but the reader should note that these were concepts already introduced to the subjects during the experiment.

Conclusions and recommendations

We identified a simple, localized vibration signal that employed only two tactors on one small area of skin, and yet conveyed a clear message consistent with the concept of object approach (i.e., it served as a tacton for looming). The signal we identified was analogous to the perceived rising frequency that is an important cue to looming in the auditory domain. Our findings have implications for the question of whether looming perceptions are modality-neutral (we think so) and whether varying the beat speed of a vibration signal is the most ecologically-valid aircraft tactile cue (we think not).

Future research is recommended to answer the following questions:

1) Is a tactile analogue of audition whose vibration frequency increases as one drifts (e.g., from the desired hover position in a helicopter) a more readily interpretable tacton during flight than the currently-employed cue (vibrations whose number of on/off pulses per second becomes greater as one moves)?
2) Can a spatial array of tactors convey looming clearly and reliably via a tacton analogous to visual flow information? If so, will the advantages of such a display compared to a simple, single-site (auditory analogue) tacton outweigh the additional weight, cost, and complexity of employing a multi-tactor array?
3) What is the accuracy of subjects' time-to-contact judgments when they are using the optimal tactons employed in this experiment or emerging from the recommended studies (questions 1 and 2, above)? The most preferred stimuli identified via further tacton research should subsequently be assessed in time-to-contact studies.

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